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TITLE: **ELECTROMAGNETIC TIME-DOMAIN CALCULATIONS IN TWO AND THREE DIMENSIONS**

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MASTER

ELECTROMAGNETIC TIME-DOMAIN CALCULATIONS IN TWO AND THREE DIMENSIONS *

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For some time, computer codes have been available for time-domain calculations of the beam-induced electromagnetic fields in axially symmetric structures (two dimensions). Recently, these codes have been extended to three-dimensional geometries. Time-domain calculations are complementary to frequency-domain calculations in accelerator designs and represent a better approach in some areas. Some of these areas will be reviewed in this paper and an introduction to the computer codes will be given.

I. Introduction

In accelerator design, electromagnetic calculations are performed in the frequency or time domain. Frequency domain calculations, reviewed in a paper by R. K. Cooper [1], have been mostly chosen in the past because of the lack of computer codes for calculations in the time domain. Time domain calculations have become more popular in recent years after computer codes for

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axially symmetric structures (two dimensions) became available around 1980 [2]. Such calculation has also become popular because there is a need to calculate beam-induced fields so that a new generation of accelerators with high charge density, short bunch, and good beam quality can be designed. Time-domain calculations are particularly suited to this need for the following reasons. First, at high beam energy where the longitudinal profile of a beam bunch remains largely unchanged, information of beam-induced fields can be contained in wake functions. A wake function is a function of time τ and is the total force experienced by a unit charge following a time τ behind the head of the exciting beam bunch [3]. Wake functions are readily calculated by a time-domain calculation and incorporated in a particle-tracking code [4]. In so doing, one can easily perform beam dynamic calculations including beam-induced fields. Second, for short bunches with high frequency content, a time-domain calculation eliminates the need of summing up information from a large number of resonant modes, as required in the case of frequency-domain calculations. Third, time-domain calculations are not restricted to resonant structures like accelerating cavities. Calculations for open structures like beam pipe transitions, as discussed in this paper, can be performed.

In this paper, calculations of the time development of beam induced electromagnetic fields of a relativistic beam will be discussed. Because of space limitation, low energy beams where particle in cell codes are required will not be discussed here. First, the computer codes are briefly reviewed in the standpoint of a user of these codes. Second, an example showing a beam traversing a step in beam-pipe size demonstrates some of the features of a time-domain calculation. Third, a calculation of the transverse effects introduced by a waveguide coupling is discussed. This is an interesting application because it has a 3D geometry and it uses a time-domain calculation to investigate a problem traditionally done in the frequency-domain.

2. Computer codes

Time-domain calculations are performed using large computer codes. In this section, the codes originating from DESY [5], among others, are chosen to be described only because they are the codes used in our Laboratory.

For geometry with axial symmetry (two dimensions), the time-domain code most used in the accelerator community is TBCI [2] written by Thomas Weiland. The starting point of this code is the discretization of Maxwell's equations by the Finite Integration Technique (FIT) algorithm. This algorithm produces a first order approximation to Maxwell's equations by replacing the line and surface integrals, appearing in Faraday's law and Ampere's law, by mean field values times path length and areas, respectively. The discretized Faraday's law and Ampere's law are then used in a leapfrog fashion to advance the electric field and magnetic field, respectively, in time.

The results of TBCI have been compared to experiments indirectly (for example, beam energy loss, beam instability limits, etc.) and show reasonable agreement. Recently, a direct experimental measurement of the induced-electric field of a 800-MeV proton exiting a beam pipe into open space has been made [6]. Fig. 1 shows a typical comparison of the experimental results with calculations using TBCI. With an estimated experimental error of approximately 15%, the agreement is good. Also, workers at the Argonne National Laboratory, using the Advanced Accelerator Test Facility, have made direct measurements of the wakefields of a disk-loaded waveguide structure. The measurements are in excellent agreement with the predictions of the TBCI code [7].

In recent years, time-domain codes have been extended to three dimensions. T3 [8] is the 3D version of TBCI. It is a member of MAFIA [5], which is a set of codes used for the design of 3D rf cavities and electromagnetic structures, including electrostatic and magnetostatic devices. Other major code groups available in 3D are ARGUS [9] and SOS [10]. The physics solvers in these 3D codes is a small fraction, approximately 20%, of the computer coding, and are similar to those used in 2D codes. The rest of the coding involves setting up the 3D geometry and preparing the results for presentation. These codes are in various development stages, and efforts are being made to accommodate larger problems and to increase computation speed.

3. Example 1: beam-pipe steps

In this section, the calculation of the beam-induced fields of a relativistic beam bunch traversing a change in beam-pipe sizes demonstrates some of the special features of a time-domain calculation [11]. A time sequence of the electric fields calculated for a step-down transition using TBCI is shown in fig. 2.

First, the geometry in the calculation has open ends on both the left and right boundaries. These open ends will present difficulties if one should try to compute the resonant-mode properties to perform a frequency-domain calculation. On the other hand, a special algorithm, called the open-boundary condition in TBCI, has allowed the simulation of an infinite beam tube on both ends of a finite geometry with very little error.

Second, a feature called the window options can be used to save computer time. For a relativistic bunch moving at the speed of light, the following conclusions can be made because of causality: no fields can ever precede the first particle of the bunch, and a particle at any position within or behind : bunch will never be affected by anything that happens behind it. In the case where only a limited range of longitudinal positions is of interest, these two observations allow solving for the fields, without introducing any errors, over only a mesh window moving with the bunch without instead of solving over the length of the geometry. The front of this window is at the longitudinal coordinate of the first particle; the back is defined by the last longitudinal position of interest. In this example of step down transition, the length of the window is equal to the length of the beam bunch, the longitudinal range of interest, and is at least twenty times shorter than the length of the structure.

Third, a picture sequence produced from a time-domain calculation like that shown in fig. 2 can help one to visualize and understand the physics of a problem.

4. Example 2: transverse effects of a waveguide coupling slot [12]

In a high-power, single-feed rf-cavity, the rf waveguide is coupled to the cavity with a large coupling slot. It is a concern that this coupling slot will break the cylindrical symmetry of the cavity substantially and introduce an appreciable transverse force on the beam. Calculations of this force, apart from the 3D nature of the problem, are difficult because the mode frequency of the accelerating mode is above the cutoff frequency of the waveguide. Calculation in the frequency domain is the method of choice for this problem, but requires an open-boundary condition at the end of the waveguide. The lack of open-boundary condition in the present 3D frequency-domain code has forced us to obtain results indirectly. In this section, an interesting solution with time-domain calculations will be presented. The need for an open-boundary condition at the waveguide is avoided by observing causality.

To study the transverse force of the accelerating mode, one needs first to establish an accelerating mode field pattern in the cavity. In a time domain calculation, this field can be induced by passing multiple bunches through the cavity. In this calculation, nine bunches were used. To ensure that the induced field is predominantly accelerating mode in nature, these bunches were chosen to have a relatively long bunch width. A long bunch will predominantly excite the mode with the lowest frequency, which is the accelerating mode. The excitation of the accelerating mode will be further enhanced by choosing a bunch frequency equal to the accelerating mode frequency so that the accelerating mode is resonantly excited.

The requirement of an outgoing-wave boundary condition was circumvented using causality considerations. Although a metal-like boundary condition was put at the end of the waveguide, it was equivalent to an outgoing-wave boundary condition for field study in the cavity until the reflections from this boundary arrive at the cavity. The time when the reflections arrive can be found analytically and with simulations. Results showed that no significant fields are traveling faster that three-fourths of the speed of light. Therefore, using a waveguide 4-m long, one can have a time window of eight rf cycles, after the bunches have passed through and before the arrival of the reflected waves, in which the field pattern of the accelerating mode can be studied.

The transverse and longitudinal forces experienced by a charge are proportional, respectively, to the transverse and longitudinal wake functions during the time window discussed above. The wake functions integrated on axis for a geometry with waveguide are shown in fig. 3. They show that a transverse force is introduced by the coupling to the waveguide. This force is in time quadrature with the accelerating force, indicating that it is magnetic in origin. With the center of a beam bunch arriving at the center of the cavity for maximum acceleration, the transverse force is zero at the center of the bunch, with the front of the bunch deflected towards the waveguide and the tail away from the waveguide. The differences in deflections for the head and tail of a bunch will be defined as the deflection shear. The deflection shears were calculated as a function of the width of the coupling slot for a bunch length of 25 ps and a beam energy of 15 MeV. Fig. 4 shows the results compared to experimental measurement [13]. Good agreement is evident.

5. Summary

Calculations of beam-induced fields in the time domain have been described. Examples are used to demonstrate the various features and applications of these calculations.

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FIGURE CAPTIONS

Fig. 1: Beam-induced electric fields of a 800-MeV proton beam exiting a beam pipe into open space. The measurement is made in open space at a location 1 m off-axis and 2 m away from the exit along the axis. The calculated results are shown as the solid curve.

Fig. 2: A picture sequence showing the electric field lines when a bunch passes a step-up transition. The density of the field lines represents the electric field strength. The bunch shape is shown under each picture.

Fig. 3: Longitudinal (solid curve) and transverse (dash-dotted curve) wake function during and after the passage of nine bunches on-axis through the cavity and waveguide arrangement. The bunch shape is represented by the dashed curve.

Fig. 4: Deflection shear introduced by the waveguide coupler as a function of the width of the coupler.

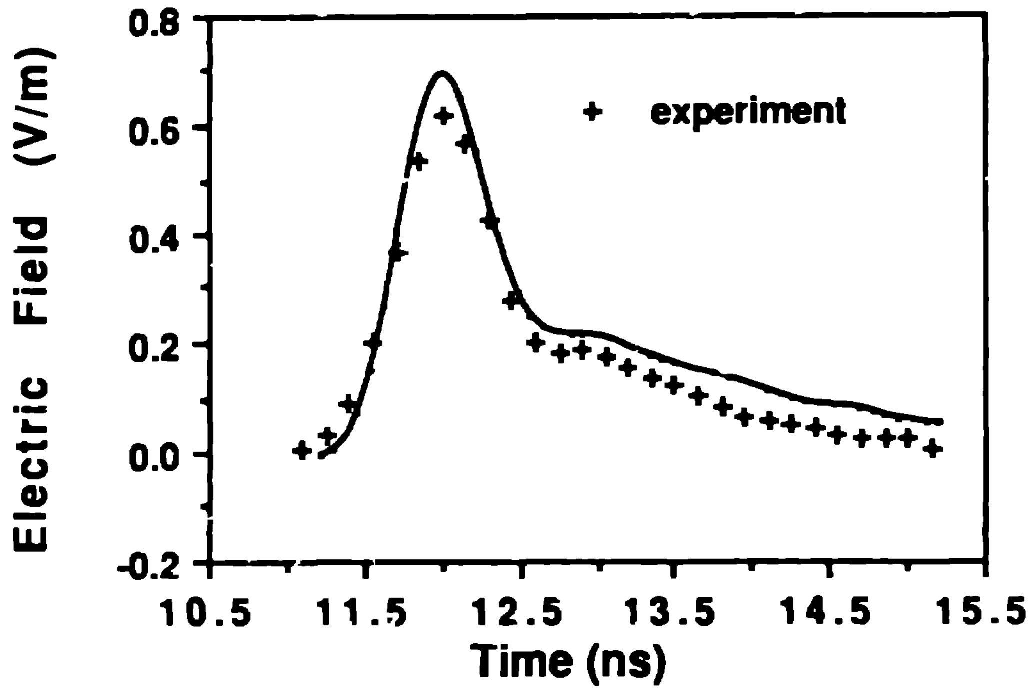
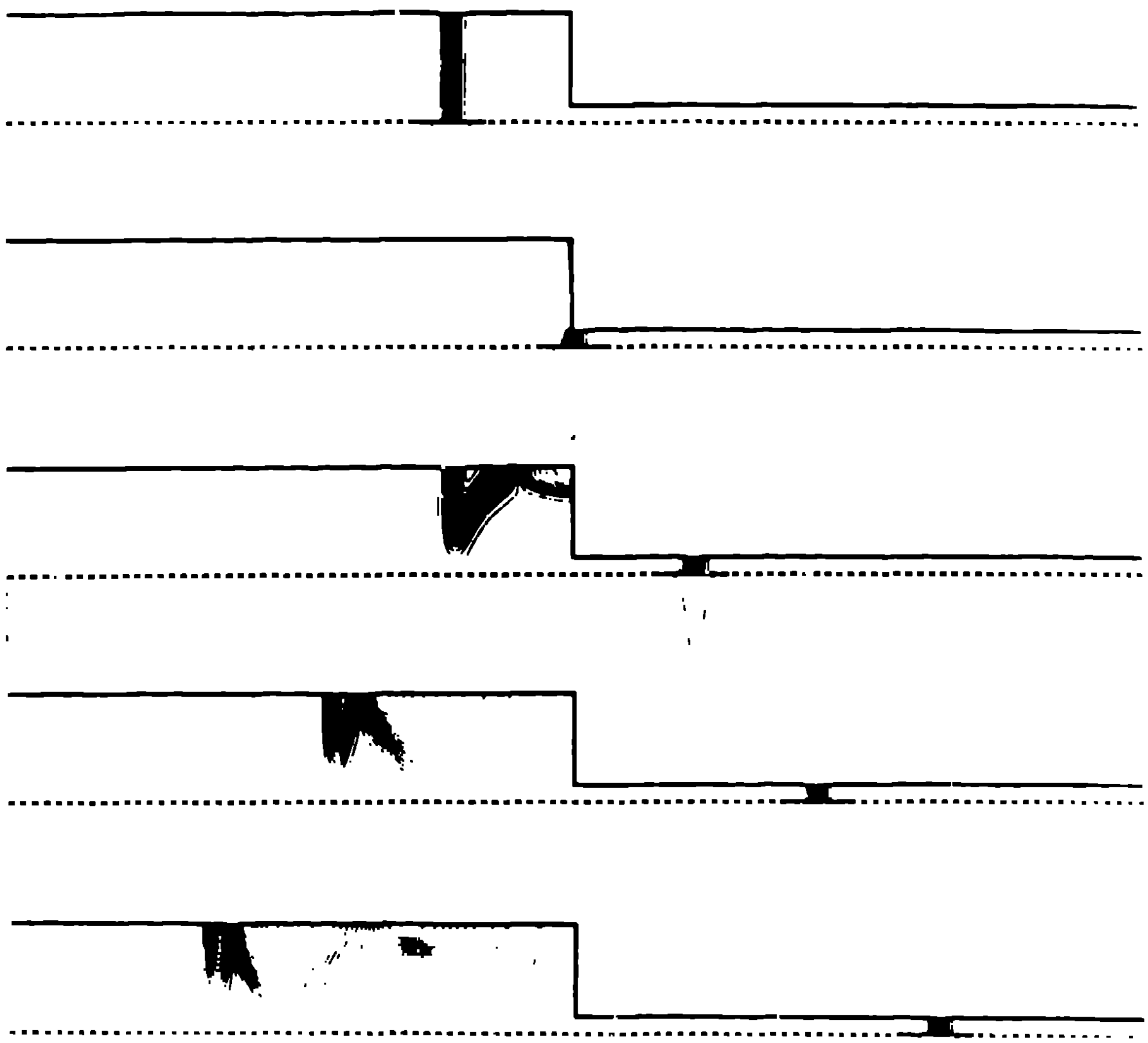
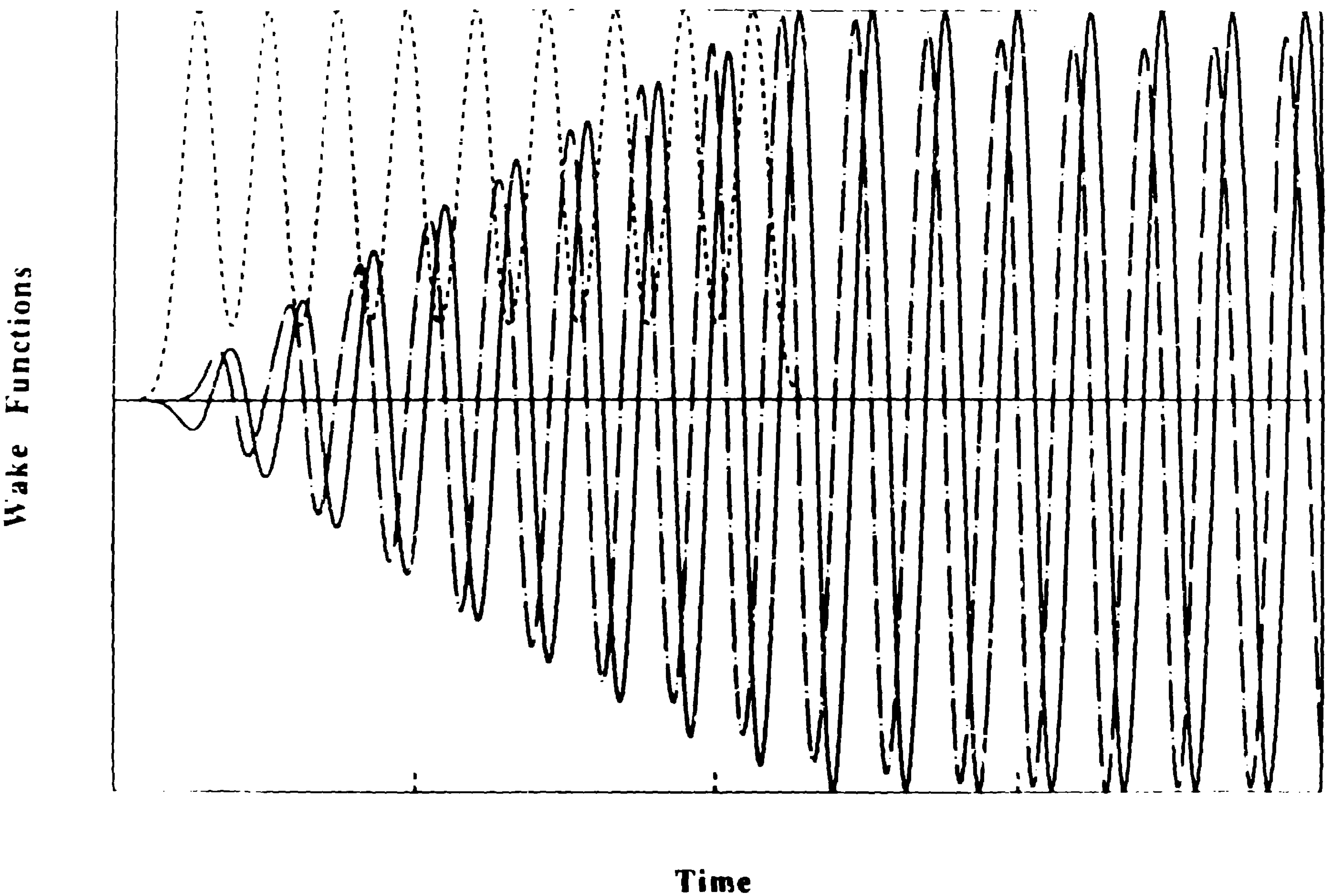

0.8
0.6
0.4
0.2
0.0
-0.2
Electric Field (V/m)
+ experiment
10.5
11.5
12.5
13.5
14.5
15.5
Time (ns)

Fig. 1




Wake Functions
Time

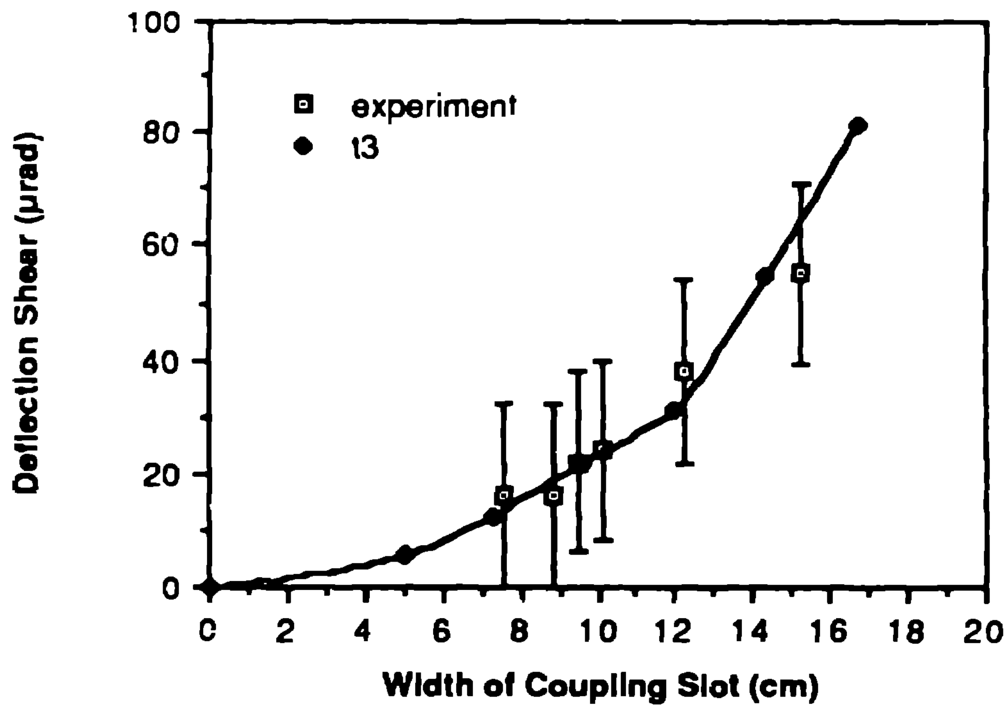

experiment
t3
Deflection Shear (μrad)
Width of Coupling Slot (cm)
0
20
40
60
80
100
0
2
4
6
8
10
12
14
16
18
20

Fig. 4